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Energy Efficiency Review and Monitoring of Special Self - Propelled Railway Rolling Stock

Ziyoda G. Mukhamedova

Abstract*: Electric power installation of a special self-propelled rolling stock used in the power supply divisions is considered in the paper; the expediency of its use for the analysis of the main energy indices, in particular, the evaluation of the efficiency of electro-hydro-mechanical units at separate and joint operation, is shown. To assess the energy efficiency, an integrated efficiency factor has been proposed that allows accounting the energy parameters of electrical installations operating in various modes. Recommendations have been given to increase the power factor of electrical installations.

Keywords: special self-propelled rolling stock, assessment, power efficiency, efficiency factor, electrical installation, block-diagram, electric motor, synchronous generator.

1. INTRODUCTION

When compared with Western European countries, there is a lag in the use of high-performance technological systems of machines and mechanisms for construction, reconstruction and renovation of a contact network, as well as small-scale mechanization tools for repair and operation of contact network devices, including rail service cars with hydraulic receivers and manipulators to mount contact structures networks; facilities and technologies for dismantling and utilization of the worked off railway racks and foundations of contact network supports.

The efficiency of rail transport depends on how completely solved is the technical problem of the state of contact network, subjected to static, dynamic, cyclic and shock loads of electric rolling stock and sharply varying meteorological environmental factors.

To maintain a regulated technical condition, repair and preventive tests of the contact network of electric railways, a special self-propelled rolling stock (SSRS) is used in the form of rail service cars and motorcars, which are the objects of energy efficiency research. They are complex, multi-element dynamic systems whose exploitation is characterized by severe operating conditions. Under these conditions, the state of the SSRS continuously changes depending on the duration and mode of operation. The change in their state, as a rule, is described by an alternating process, which is an alternation of time intervals for joint and separate operation of mechanical, hydraulic and electrical installations, the modes of which are interconnected and determine the consumption of fuel and energy resources.

The need for a market economy requires an intensive development of the energy efficiency of rail transport infrastructure. Currently, a significant part of the infrastructure has exhausted its resources and requires a step-by-step reconstruction and modernization to increase the efficiency of the SSRS use, reduction of its operating costs and transition to resource-saving technologies.

Improving the efficiency of diesel fuel consumption of the SSRS at the maintenance and repair of the contact network is one of the components of the program to reduce the loss of fuel and energy resources of railways, which indicates the relevance of the chosen research direction.

One of the main indicators of the energy efficiency of rail service cars is the coefficient of efficiency, on which energy costs significantly depend. The estimates of the coefficient of efficiency of rail service cars are outdated, as their structural, hydraulic and electromechanical installations have changed; the coefficient of efficiency of the internal combustion engine, of synchronous generator and three-phase asynchronous electric motors installed on the rail service cars, the modes of contact network repair technology due to the use of ready-made block units of contact suspensions have been improved. All this affects the coefficient of efficiency and as a result, the fuel consumption of rail service cars.

Let us estimate in general terms the coefficient of efficiency of a rail service car, taking into account the components of the engine's work on raising and turning the installation platform, turning the cargo crane, hydraulic electric pump and electro-hydraulic pusher.

The power scheme of the rail service cars is a series of successive and parallel connections of the energy conversion installations of the system shown in Figure 1 as a block diagram. The rail service car is an autonomous rolling stock consisting of a YaMZ-238B ??? ЯМЗ–238Б type internal combustion engine driving a synchronous generator (SG) of ECC – 62–4У2 type. SG feeds a three-phase crane asynchronous electric motor (AM) of *MTF* – 012–6 type with a phase rotor, a platform for AM turning, AM of НШ–10 type of the hydraulics pump and AM of ТЭ–25 type of the electro-hydraulic pusher [1,2].

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Ziyoda G. Mukhamedova, Tashkent Institute of Engineers of Railway Transport (TIERT), Tashkent, Uzbekistan

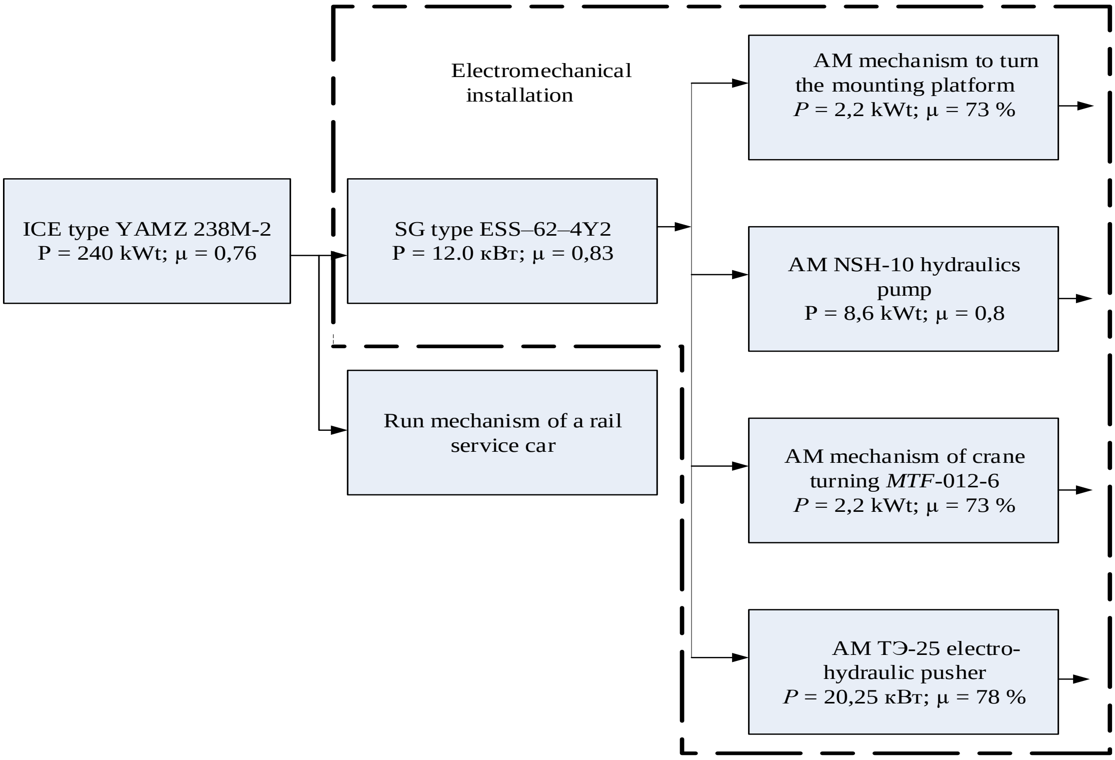

Figure 1 - Block diagram of the main power installation of a rail service car

As seen from Figure 1, the power balance at different points of the scheme is: at the output of the internal combustion engine or at the input of the synchronous generator (SG) P_{sg}, at the output of SG or at the input of AM of the rotation mechanism of mounting platform P_{mmp}, the hydraulics pump drive mechanism P_{pdm}, the crane rotation mechanism P_{crm} and electro-hydraulic pusher P_{ehp}. All the power of the internal combustion engine of the rail service car $P_{ам}$ is spent on the run of rail service car P_{run} and the installation, maintenance and repair work, of total power of $\sum P_{eps}$. Therefore, the average weighted coefficient of efficiency of the rail service car is characterized by the expression:

$$\eta_{am} = \frac{P_{run} + \sum P_{eps}}{P_{ice}} * 100\%. \quad (1)$$

The capacity of the rail service car, spent on the electro-hydro-mechanical operation of the P_{eps} drive only, is characterized by the expression:

$$\eta_{am} = \frac{\sum_i P_{eps}\eta_i}{P_{ice}} = \eta_{ehm}\gamma_i$$

or

$$\eta_{am} = \frac{\sum_i P_{eps}\eta_i}{\sum_i \frac{P_{eps}\gamma_{pni}}{\eta_{am}}} = \frac{1}{\sum_i \frac{\gamma_{pni}}{\eta_{ampi}}}\eta_{ehm}\gamma_i, \quad (2)$$

where P_{eps}, P_{ice}, η_{ampi} are the expended power and the coefficient of efficiency of the *i*-th electric motor of the rail service car; γ_{pni}, η_{ampi} are the proportions of expended and useful power of the *i*-th electric motor in the corresponding total power of the rail service car.

Analysis of the above expression (2) and the block diagram of the main power installations in Figure 1 show the following: the average weighted coefficient of efficiency of each power installation depends on the coefficient of efficiency of the associated group and power distribution between them. The greater the coefficient of efficiency of a single power installation and the greater the proportion of power of the installation with a high efficiency, the higher the average weighted coefficient of efficiency of this set of installations. Since the overall efficiency of the power circuit depends on the product of the average weighted efficiency of successively connected power installations, the more the average weighted efficiency of a set of installations connected in parallel, the higher the overall efficiency of the rail service car.

As is known the generalized efficiency of power installations (internal combustion engines, synchronous generator and AD group) connected successively, is equal to the product of partial efficiency:

$$\eta_{ei} = \eta_{ice} * \eta_{sg} * \eta_{eps}, \quad (3)$$

Where, η_{ice} is the efficiency of the internal combustion engine; η_{sg} is the efficiency of the synchronous generator; η_{eps} is the average weighted efficiency of the electromechanical installation.

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The average weighted efficiency of the electromechanical installation of the rail service car (Figure 1) is characterized by the expression:

$$\eta_{eps} = \frac{\sum_{i=1} P_{ami} t_i}{P_{sg} \sum t_i} = \frac{P_{dap} t_{dap} + P_{dhp} t_{dhp} + P_{dct} t_{dct} + P_{ehp} t_{ehp}}{\dfrac{P_{sg}(t_{dap} + t_{dhp} + t_{dct} + t_{ehp})}{2}}, \qquad (4)$$

where $P_{sg}, P_{dap}, P_{dhp}, P_{dct}, P_{ehp}$ are the nominal powers of the synchronous generator, the drive of the assembly platform, the drive of the hydraulics pump, the drive for the crane turning, and the drive of the electro-hydraulic pusher, respectively; 2 is the metering factor for receivers during the expected maximum load per hour at $t \geq 0,5$.

Substituting into (4) the installed engines capacities and average chronometric times of operation of each AM, for example, at typical preparing for the autumn-winter period for the 3rd quarters separately for 2016–2018, (data given by the Railway Engineering Division of the Mechanization Department of "Uzbekistan Railways", Table 1, taking into account the fact that the simultaneous operation of a crane turning and mounting platform is prohibited [2,7]), we get:

operation without the crane turning

$$\eta_{eps} = \frac{2,2*37,3+8,6*66,3+0,25*66,6}{\dfrac{12(37,3+66,3+66,6)}{2}}*100\% = 65,5\%$$

operation without the assembly platform

$$\eta''_{eps} = \frac{8,6*66,3+2,2*30,6+0,25*66,6}{\dfrac{12(66,3+30,2+66,6)}{2}}*100\% = 66,68\%.$$

Table 1 - Chronometric operation time of electric motors at typical preparing for the autumn-winter period

Types of Electric drives / **For the 3rd quarters of the year**	**Synchronous generator, ЕСС-62-4У2, hour** P = 12k W; η = 0,8; m = 238kg	**Electric motor of assembly platform** P = 2,2kW; η = 0,77; n = 1500 rev/min; cos φ = 0,79	**Electric motor NSH - 10 of the drive of hydraulics pump, hour** P = 8,6kW; η = 0,8; η = 2400 rev/min; m = 2,58 kg; cos φ = 0,92	**Electric motor of a crane turning, hour** ***MTF* – 012 - 6** P = 2,2kW; η = 0,73; n = 895 rev/min; cos φ = 0,76	**Electric motor ТЭ-25 of the hydraulics pusher, hour** P = 0,25kW; n = 2800 rev/min; m = 8,8 kg; cos φ = 0,82; η = 0,78
2016	66,0	36,0	66,0	30,0	66,0
2017	69,0	39,0	69,0	33,0	69,0
2018	66,0	37,0	64,0	29,0	65,0
Quarterly average	67,0	37,3	66,3	30,6	66,6

It is appropriate to note that due to the difficulty of determining the technological schedule of more than 22 types of maintenance and repair work performed by all electric motors with different loads of the rail service car, it is advisable to determine the design power of the synchronous generator by [6]:

$$P_{calc} = \sum_{1}^{n} \frac{P_y k_c}{\eta_n} + \sum_{1}^{m} \frac{P'_y k_c t}{0,5\eta_m}, \qquad (5)$$

where P_y is the installed capacity of each of the receivers operating under the expected maximum load at t> 0.5 h, kW; η is the efficiency of the electric receiver; k_c is the load factor; P'_y is the installed capacity of each of m receivers involved in the formation of the maximum load and operating at the maximum less than 0.5 h, kW; t is the duration of continuous operation of each of electric receivers with the power P' (t<0,5 h).

The above-obtained value of the average weighted efficiency of the electromechanical part of the rail service car η_{eps} (4) shows that the installed power of the synchronous generator and the group of three-phase AM, in general, corresponds to the load diagrams and overload capabilities of its electromechanical part.

To improve the energy efficiency of electric drives, it is advisable for each installed AM to provide for an increase in cosφ by connecting special compensating capacitors according to the scheme in Figure 2.

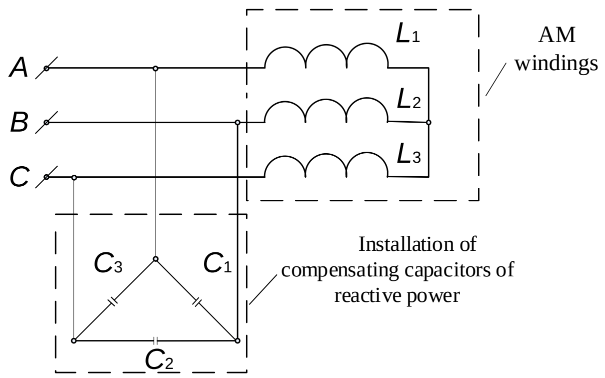

Figure 2 - Diagram of the connection of compensating capacitors C_1, C_2, C_3 to the AM windings.

The magnitude of the compensating capacitors $C_1 = C_2 = C_3 = C$ connected by the "triangle" scheme is calculated separately for each electric motor using the formula [5]:

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$$C = \frac{P(\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2)}{\omega U^2}, \quad (6)$$

where P is the engine power, W; φ_1 is the angle of current vector displacement relative to the voltage, specified by cosφ of the engine; $\varphi_2 = \arccos 0{,}96$ is the current phase shift of the motors relative to the voltage corresponding to the recommended cosφ according to the ПУЭ; ω is the angular frequency, rad/s; U - is the nominal linear voltage of the motor, W.

$\varphi_2 = \arccos 0{,}96$ – сдвиг фазы тока двигателей относительно напряжения соответствующий, рекомендуемому cosφ по ПУЭ;

The calculated values of the specified AM capacitors and currents are given in Table 2.

Table 2 - Calculated values of electric motor currents before and after switching on the compensating capacitors

Capacity ad AM cosφ	C, mkF	AM currents before and after switching on the capacitors, A
Assembly platform, P=2,2 kW, cosφ=0,79	23,0	7,32/6,03
Hydraulics pump, P=8,6 kW, cosφ=0,92	24,0	24,59/23,57
Crane turning, P=2,2 kW, cosφ=0,76	27,0	7,61/6,032
Electric hydraulic pusher, P=0,25 kW, cosφ=0,82	2,24	0,80/0,68

According to the calculation results, it is seen that the connection of compensating capacitors to the executive motors leads to a 20% decrease in the stator currents of the electric motors.

From the above calculations it follows that in the development of new types of rail service cars or the modernization of existing ones, the question arises of choosing the type of electric drives and the power supply synchronous generator with higher capacity [1, 2]. For a more generalized determination of the effectiveness of electric drives of the SSRS it is appropriate to use an integral coefficient of efficiency to determine their optimal parameters. The integral coefficient of efficiency is determined based on the probability of the drive operation in various modes using formula [3.8]:

$$Z(M,n) = \frac{\sum_{i=1} t(M_i,n)}{\sum_{i=1} T_i}, \quad (7)$$

where $\sum_{i=1} t(M_i,n)$ is the total operating time of the drive in (*M*, *n*)-th mode of operation, h; $\sum t_i$ is the total operating time of electric drives; $M_i = \frac{P_{нi}}{\omega_{нi}}$ is the electromagnetic moment, Nm, calculated by the following formula:

$$M = \frac{\sum_i M_i^2 t_i}{\sum_{i=1}^{n} t_i}, \quad (8)$$

$P_{нi}, \omega_{нi}$ is the nominal capacity and angular frequency of the *i*-th electric motor; *n* is the rotational rate, revolution per minute.

The costs of the SSRS operation are defined [4]:

$$C_{exp} = C_d + C_{ehm} + C_{tenz}, \quad (9)$$

where C_d is the cost of the SSRS run, rubles; C_{ehm} is the costs of operation of electric drives of electric, hydraulic and mechanical installations, rubles; C_{tenz} is the cost of maintenance and repair of the SSRS, rubles.

Total costs of the SSRS are the costs of fuel and lubricants, which depend on the mode of operation:

$$C_{ij} = \frac{Mn}{\eta_j} t_j P_{flr} = \frac{Mn}{\eta_j} Z_j P_{flr} T_i, \quad (10)$$

where η_j is the instantaneous coefficient of efficiency; t_j is the operation time in the *j*-th mode, hour; P_{flr} is the reduced price of fuel and lubricants, rubles; Z_j is the probability of SG drive operation in the *j*-th mode; $\sum T_i$ is the running time of the rail service car drives, hour.

An analysis of chronometric measurements of the operating time of each installation of the rail service car shows [8] that for a preliminary assessment, the instantaneous coefficient of efficiency of the drive can be replaced by its energy factor. Such a replacement makes it possible to estimate its efficiency without calculation of the efficiency of the SG drive operating according to (2), in the incomplete capacity mode [7].

Hence, the following can be obtained [4]:

$$C_{ij} = \frac{Mn}{P_j F_j} t_j P_{flr} = \frac{Mn}{PF} Z_j P_{flr} T_i, \quad (11)$$

where $P_j F_j$ is the energy factor of operation of each electric drive in different modes, calculated according to the data in Table 1.

The cost of the rail service car time operation is determined by the following expression, in rubles:

$$C_{ij} = P_{flr} T \sum_{F=0}^{M_{max}} \sum_{n=-n_{con}}^{M_{con}} \left(\frac{Z_{flr} Mn}{PF}\right) = \frac{M_{max} n_{con}}{\int \eta} P_{flr} T, \quad (12)$$

Where n_{con} is the constructive engine rate of each installation, rpm;

$\int \eta$ is the integral efficiency of the rail service car determined by the ratio:

$$\int \eta = \frac{M_{max} n_{con}}{\sum_{M=0}^{M_{max}} \sum_{n=-n_{con}}^{n_{con}} \left(\frac{Z_{гсм} Mn}{PF}\right)}, \quad (13)$$

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Expression (13) characterizes the integral efficiency from the point of view of using the maximum capacity of each unit, and from the point of using them in various under-used modes, since $T, M_{\max}, n_{con}$ are the values that do not depend on the type of drives and operating modes of the SSRS [10]. Note that the integral efficiency is a relative value, and the object always runs at a constructional rate under different loads. Thus, the integral efficiency takes into account not only the efficiency of the electric drive, but also the mode of operation of the rail service car [9], that is, it is an integral part of the criterion of current costs for the SSRS operating.

2. CONCLUSION

1. The proposed criterion for estimating the energy efficiency of the SSRS — the integrated coefficient of efficiency — allows one to take into account the energy parameters of electric drives (engine efficiency and cosφ) for various operating modes and the mode of the SSRS.
2. It is advisable to use the integrated efficiency in the development of new and the use of reconstructed SSRS to reduce fuel consumption and save other resources.
3. The connection of compensating capacitors to the installed motors reduces the stator winding current by 20%.

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